THE NATURAL AND ARTIFICIAL DISINTEGRATION OF THE ELEMENTS

AN ADDRESS BY

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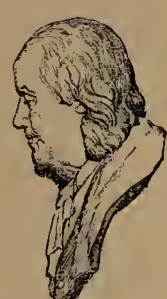

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THE NATURAL AND ARTIFICIAL DISINTEGRATION OF THE ELEMENTS

By Professor Sir ERNEST RUTHERFORD, Kt., D. Sc., LL. D., Ph. D., D. Phys., F. R. S.

IT is not my intention in this paper to give a detailed account of the natural disintegration of the radio elements or of the methods employed to effect the artificial disintegration of certain light elements. I shall assume that you all have a general knowledge of the results of these investigations, but I shall confine myself to a consideration of the bearing of these results on our knowledge of the structure of the nuclei of atoms.

There is now a general agreement that the atoms of all elements have a similar electrical structure, consisting of a central positively charged nucleus surrounded at a distance by the appropriate number of electrons. From a study of the scattering of α particles by the atoms of matter and from the classical researches of Moseley on X-ray spectra, we know that the resultant positive charge on the nucleus of any atom, in terms of the fundamental unit of electronic charge, is given numerically by the atomic or ordinal number of the element, due allowance being made for missing elements. We know that with few exceptions all nuclear charges, from 1 for the lightest atom, hydrogen, to 92 for the heaviest element, uranium, are represented by elements found in the earth. The nuclear charge of an element controls the number and distribution of the external electrons, so that the properties of an atom are defined by a whole number, representing its nuclear charge, and are only to a minor degree influenced by the mass or atomic weight of the atom.

This minute but massive nucleus is, in a sense, a world of its own which is little, if at all, influenced by the ordinary physical and chemical forces at our command. In many

respects, the problem of nuclear structure is much more difficult than the corresponding problem of the arrangement and motions of the planetary electrons, where we have a wealth of available information, both physical and chemical, to test the adequacy of our theories. The facts known about the nucleus are few in number and the methods of attack to throw light on its structure are limited in scope.

It is convenient to distinguish between the properties assigned to the nucleus and the planetary electrons. The movements of the outer electrons are responsible for the X-ray and optical spectra of the elements and their configuration for the ordinary physical and chemical properties of the element. On the other hand, the phenomena of radioactivity and all properties that depend on the mass of the atom are to be definitely assigned to the nucleus. From a study of the radioactive transformations, we know that the nucleus of a heavy atom not only contains positively charged bodies but also negative electrons, so that the nuclear charge is the excess of positive charge over negative. In recent years, the general idea has arisen that there are two definite fundamental units that have to do with the building up of complex nuclei, viz., the light negative electron and the relatively massive hydrogen nucleus which is believed to correspond to the positive electron.

This view has received very strong support from the experiments of Aston on Isotopes in which he has shown that the masses of the various species of atoms are represented nearly by whole numbers in terms of $O=16$. From the general electric theory, it is to be anticipated that the mass of the hydrogen nucleus in the nucleus structure will be somewhat less than its value 1.0077 in the free state on account of the very close packing of the charged units in the concentrated nucleus. From Aston's experiments, it appears that the average mass of the hydrogen nucleus, or proton as it is now generally called, is very nearly 1.000 under these conditions. We should anticipate that the whole number rule found by Aston would hold only to a first approximation, since the

mass of the proton must be to some extent dependent on the detailed structure of the nucleus. In the case of tin and xenon Aston has already signalized a definite departure from the whole number rule, and no doubt a still more accurate determination of the masses of the atoms will disclose other differences of a similar kind.

While our present evidence indicates that the proton and electron are the fundamental constituents of the nucleus, it is very probable that secondary combining units play a prominent part in nuclear constitution. For example, the expulsion of helium nuclei from the radioactive bodies indicates that the helium nucleus of mass 4 is probably a secondary unit of great importance in atom building. On the views outlined, we should expect the helium nucleus of charge 2 to be built up of four protons and two electrons. The loss of mass in forming this nucleus indicates that a large amount of energy must be liberated during its formation. If this be the case, the helium nucleus must be such a stable structure that the combined energy of four or five of the swiftest α particles would be necessary to effect its disruption. Such a deduction is supported by our failure to observe any evidence of disintegration of the swift particle itself, whether it is used to bombard matter or whether the α particle is used to bombard other helium atoms.

On these views, we should anticipate that the nucleus of radium of atomic number 88 and atomic weight 226 contains in all 226 protons of mass 1 and 138 electrons. While this gives us the numerical relation between the two fundamental units, we have, at present, no definite information of their arrangement in the minute nuclear volume, nor of the nature and magnitude of the forces that hold them together. We should anticipate that many of the protons and electrons unite to form secondary units, *e. g.* helium nuclei, and that the detailed structure of the nucleus may be very different from that to be expected if it consists of a conglomeration of free protons and electrons.

It is thus of great importance to obtain definite evidence of the nature and arrangement of the components of the nucleus and of the forces that hold them in equilibrium. We shall now consider some of the lines of evidence which throw light on the actual dimensions of the nucleus and the law of force operative in its neighborhood; the structure and modes of vibration of the nucleus, together with the effects observed when some light nuclei are disintegrated by bombardment with α particles.

DIMENSIONS OF THE NUCLEI AND THE LAW OF FORCE

The conception of the nucleus atom had its origin in 1911 in order to explain the scattering of an α particle through a large angle as the result of a single collision. The observation that the α particle is in some cases deflected through more than a right angle as the result of an encounter with a single atom first brought to light the intense forces that exist close to the nucleus. Geiger and Marsden showed that the number of particles scattered through different angles was in close accord with the simple theory which supposed that, for the distance involved, the α particle and nucleus behaved like charged points, repelling each other according to the law of the inverse square. The accuracy of this law has been independently verified by Chadwick, so that we are now certain that in a region close to the nucleus the ordinary laws of force are valid.

These scattering experiments also gave us the first idea as to the probable dimensions of the nuclei of heavy atoms, for it is to be anticipated that the law of the inverse square must break down if the α particle approaches closely to or actually enters the nuclear structure. This variation in the law of force would show itself by a difference between the observed and calculated numbers of α particles scattered through large angles. Geiger and Marsden, however, observed no certain variation even when the α particles of range about 4 cms. were scattered through 100° by a gold nucleus. In such an encounter, the closest distance of approach of the α particle to

the center of the nucleus is about 5×10^{-12} cm., so that it would appear that the radius of the gold nucleus, assumed spherical, could not be much greater than this value.

There is another argument, based on radioactive data, which gives a similar value for the dimensions of the radius of a heavy atom. The α particle escaping from the nucleus increases in energy as it passes through the repulsive field of the nucleus. To fix a minimum limit, suppose the α particle from uranium, which is the slowest of all α particles expelled from a nucleus, gains all its energy from the electrostatic field. It can be calculated on these data that the radius of the uranium nucleus cannot be less than 6×10^{-12} cm. This is based on the assumption that the forces outside the nucleus are repulsive and purely electrostatic. If, as seems not unlikely, there also exist close to the nucleus strong attractive forces, varying more rapidly than an inverse square law, the actual dimensions may be less than the value caculated above.

At this stage of our knowledge it is of great importance to test whether the law of force breaks down for the distance of closest approach of an α particle to a nucleus. This can be done by comparing the observed with the calculated number of α particles scattered through angles of nearly 180°. It seems almost certain that the inverse square law must break down when swift α particles are used. This can be seen from the following argument. If an α particle, of the same speed as that ejected during the transformation of uranium, is fired directly at the uranium nucleus, *it must penetrate into the nuclear structure.* If a still swifter α particle is used, *e. g.* that from radium C, which has about twice the energy of the uranium α particle, it is clear that it must penetrate still more deeply into the nuclear structure. This is based on the assumption that the field due to a nucleus is approximately symmetrical in all directions. If this is not true, it may happen that only a fraction of the head-on collisions may be effective in penetrating the nucleus. It is hoped soon to attack this difficult problem experimentally.

We have so far dealt with collisions of an α particle with a heavy atom. We know, however, from the results of Rutherford, Chadwick and Bieler that in a collision of an α particle with the lightest atom, hydrogen, the law of the inverse square breaks down entirely when swift particles are used. Not only are the numbers of H nuclei set in swift motion much greater than is to be expected in the simple-point nucleus theory, but the change of number with the velocity of the α particle varies in the opposite way from the simple theory. Such wide departures between theory and experiment are only explicable if we assume either that the nuclei have sensible dimensions or that the inverse square law of repulsion entirely breaks down in such close collisions. If we suppose the complexity in structure and in laws of force is to be ascribed to the α particle rather than to the hydrogen nucleus, Chadwick and Bieler, as the result of a careful series of experiments, concluded that the α particle behaved as if it were a perfectly elastic body, spheroidal in shape with its minor axis 4×10^{-13} cm. in the direction of motion and major axis 8×10^{-13} cm. Outside this spheroidal region the forces fell off according to the ordinary inverse square law, but inside this region the forces increased so rapidly that a particle was reflected from it as from a perfectly elastic body. No doubt such a conception is somewhat artificial, but it does serve to bring out the essential points involved in the collision, viz., that when the nuclei approach within a certain critical distance of each other, forces come into play which vary more rapidly than the inverse square. It is difficult to ascribe this break-down of the law of force merely to the finite size or complexity of the nuclear structure or to its distortion, but the results rather point to the presence of new and unexpected forces which come into play at such small distances. This view has been confirmed by some recent experiments of Bieler in the Cavendish Laboratory in which he has made, by scattering methods, a detailed examination of the law of force in the neighborhood of a light nucleus like that of aluminum. For this purpose he

compared the relative number of α particles scattered within the same angular limit from aluminum and from gold. For the range of angles employed, viz., up to 100°, it is assumed that the scattering of gold follows the inverse square law. He found that the ratio of the scattering in aluminum compared with that in gold depended on the velocity of the α particle. For example, for an α particle of 3.4 cms. range, the theoretical ratio was obtained for angles of deflection below 40° but was about 7 per cent lower for an average angle of deflection of 80°. On the other hand, for swifter particles of range 6.6 cms. a departure from the theoretical ratio was much more marked and amounted to 29 per cent for an angle of 80°. In order to account for these results he supposes that close to the aluminum nucleus an attractive force is superimposed on the ordinary repulsive forces. The results agreed best with the assumption that the attractive force varies according to the inverse fourth power of the distance and that the forces of attraction and repulsion balanced at about 3.4×10^{-13} cm. from the nuclear center. Inside this critical radius the forces are entirely attractive; outside they are repulsive.

While we need not lay too much stress on the accuracy of the actual value obtained or of the law of attractive force, we shall probably not be far in error in supposing the radius of the aluminum nucleus is not greater than 4×10^{-13} cm. It is of interest to note that the forces between an α particle and a hydrogen nucleus were found to vary rapidly at about the same distance.

It thus seems clear that the dimensions of the nuclei of light atoms are small, and almost unexpectedly small in the case of aluminum when we remember that 27 protons and 14 electrons are concentrated in such a minute region. The view that the forces between nuclei change from repulsion to attraction when they are very close together seems very probable, for otherwise it is exceedingly difficult to understand why a heavy nucleus with a large excess of positive charge can hold together in such a confined region. We shall see that the evidence from various other directions supports such a

conception, but it is very unlikely that the attractive forces close to a complex nucleus can be expressed by any simple power law.

RADIOACTIVE EVIDENCE

A study of the long series of transformations which occur in uranium and thorium provides us with a wealth of information on the modes of disintegration of atoms, but unfortuately our theories of nuclear structure are not sufficiently advanced to interpret these data with any detail. The expulsion of high speed α and β particles from the radioactive nucleus gives us some idea of the powerful forces resident in the nucleus, for it can be estimated that the energy of emission of the α particle is in some cases greater than the energy that would be acquired if the α particle fell freely between two points differing in potential by about 4 million volts. The energies of the β and γ rays are on a similar scale of magnitude.

Notwithstanding our detailed knowledge of the successive transformation of the radio-elements, we have not so far been able to obtain any definite idea of their nuclear structure, while the cause of the disintegration is still a complete enigma. In comparing the uranium, thorium, and actinium series of transformations, one cannot fail to be struck by the many points of similarity in their modes of disintegration. Not only are the radiations similar in type and in energy, but, in all cases, the end product is believed to be an isotope of lead. This remarkable similarity in the modes of transformation is especially exemplified in the case of the "C" bodies, each of which is known to break up in at least two distinct ways, giving rise to branch products. For example, thorium C emits two types of α rays, 65 per cent of range 8.6 cms. and 35 per cent of range 4.8 cms., and in addition some β rays.

In order to explain these results, it has been suggested that a fraction of the atoms of thorium C break up first with the expulsion of an α particle and the resulting product then emits a β particle. The other fraction breaks up in a reverse way, first expelling a β particle, while the subsequent product emits

an α particle. Similar dual changes occur in radium C and actinium C, although the relative number of atoms in each branch varies widely for the different elements.

This remarkable similarity between the "C" bodies is still further emphasized by the recent discovery of Bates and Rogers that both radium C and thorium C give rise in small numbers to other groups of α particles, some of them moving at very high speeds.

It has often been a matter of remark that the radioactive properties of the "C" bodies seem to depend more on the atomic number, *i. e.*, the nuclear charge, than on the atomic weight. Confining our attention to radium C and thorium C, which are best known, both have a nuclear charge 83, but the atomic mass of radium C is 214 and of thorium C 212. The nucleus of radium C thus contains two protons and two electrons more than that of thorium C. If it were supposed that the nuclei of these elements consisted of a large number of charged units in ceaseless and irregular motion, it is to be anticipated that the addition of the protons and electrons to the complex structure would entirely alter the nuclear arrangement and consequently its stability and mode of transformation. On the other hand, we find that the modes of transformation of these two nuclei have striking and unexpected points of resemblance which are in entire disaccord with such a supposition. We can, however, suggest a possible explanation of this anomaly by supposing that the α and β particles which are liberated from these elements are not built deep into the nuclear structure but exist as *satellites* of a central core which is common to both elements. These satellites, if in motion, may be held in equilibrium by the attractive forces arising from the core, and these forces would be the same for both elements. On this view the manifestations of radioactivity are to be ascribed not to the main core, but to the satellite distribution, which must be somewhat different for the two elements although possibly showing many points of similarity. It must be admitted that a theory of this

kind is highly speculative, but it does provide a useful working hypothesis, not only to account for the similarity of the modes of transformation of the two elements but also immediately suggests a possible explanation of the liberation of a number of α particles of different ranges from the same element. There are two ways of regarding this question. We may in the first place suppose that a certain amount of surplus energy has to be liberated in the disintegration and that this energy may be given to any one of a number of satellites. There will be a certain probability that any particular particle will be given this energy, and on this will depend the relative number of particles in the different α ray groups. The ultimate energy of ejection of an α particle will depend on its position in the field of force surrounding the inner core at the moment of its liberation. On the other hand, we may suppose that the same α particle is always ejected but that the particle may occupy in the atom one of a number of "stationary" positions analogous to the "stationary states" of the electrons in Bohr's theory of the outer atom. This rests on the assumption that all the atoms will not be identical in satellite structure but there will be a number of possible "excited" states of the atom as a consequence of the previous disintegrations. This satellite theory is useful in another connection. It has been suggested that possibly the high frequency γ rays from a radioactive atom may arise not from the movement of the electrons as ordinarily supposed, but from the transfer of α particles from one level to another. In such a case, the difference in energies between the various groups of α particles from radium C and thorium C should be connected by the quantum relation with the frequencies of prominent γ rays. The evidence at present available is not definite enough to give a final decision on this problem, but points to the need of very accurate measurements of the energies of the various groups of α particles. On account of the relatively small number of particles in some of the groups, this is difficult of accomplishment.

In considering the satellite theory in connection with the radioactive bodies, it is at first sight natural to suppose, since the end product of both the radium and thorium series is an isotope of lead, that one of the isotopes of lead forms the central core. It may, however, well be that the radioactive processes cease when there are still a number of satellites remaining. If this be so, the core may be of smaller nuclear charge and mass than that of lead. From some considerations, described later, this core may correspond to an element near platinum of number 77 and mass 192.

FREQUENCY OF VIBRATION OF THE NUCLEUS

One of the most interesting and important methods of throwing light on nuclear structure is the study of the very penetrating γ rays expelled by some radioactive bodies. The γ rays are identical in nature with X-rays, but the most penetrating type of rays consists of waves of much higher frequency than can be produced in an ordinary X-ray tube. The work of the last few years has indicated very clearly that the major part of the γ radiation from bodies like radium B and C originates in the nucleus. A determination of the frequencies of the γ rays thus gives us direct information on the modes of vibration of parts of the nuclear structure. The frequency of some of the softer γ rays excited by radium B and radium C was measured by the crystal method by Rutherford and Andrade, but it is difficult, if not impossible, by this method to determine the frequencies of the very penetrating rays. Fortunately, due largely to the work of Ellis and Fraulein Meitner, a new and powerful method has been devised for this purpose. It is well known that the β rays from radium B and radium C give a veritable spectrum in a magnetic field, showing the presence of a number of groups of β rays each expelled with a definite speed. It is clear that each of the groups of β rays arises from conversion of the energy of a γ ray of definite frequency into a β ray in one or other of the electronic levels in the outer atom. The energy w required to move an

electron from one of these levels to the outside of the atom is known from a study of X-ray absorption spectra. The frequency ν of the γ ray is thus given by the quantum relation $h\nu = E + w$, where E is the measured energy of the β particle.

Since each γ ray may be converted in any one of the known electronic levels in the outer atom, a single γ ray is responsible for the appearance of a number of groups of β rays, corresponding to conversion in the K, L, M, etc., levels. In this way, an analysis of the β ray spectrum allows us to fix the frequency of the more intense γ rays which are emitted from the nucleus. The energy of the shortest wave measured in this way by Ellis corresponds to more than two million volts, while other evidence shows that probably still shorter waves are emitted in small quantity from radium C.

Ellis and Skinner have shown that the energies of these rays show certain combination differences, such as are so characteristic of the energies of the X-rays arising from the outer electrons. A series of energy levels may thus be postulated in the nucleus similar in character to the electron levels of the outer atom, and the γ rays have their origin in the fall either of an electron or of an α particle between these levels. This is a significant and important result, indicating that the quantum dynamics can be applied to the nucleus as well as to the outer electronic structure.

The probability of levels in the nuclear structure is most clearly seen on the satellite hypothesis, but in our ignorance of the laws of force near the core we are at the moment unable to apply the quantum dynamics directly to the problem. The outlook for further advances in this direction is hopeful, but is intimately connected with a further development of our knowledge of the laws of force that come into play close to the nucleus in the region occupied by the satellites.

ARTIFICIAL DISINTEGRATION OF ELEMENTS

We have seen that it is believed that the nuclei of all atoms are composed of protons and electrons and that the number of

each of these units in any nucleus can be deduced from its mass and nuclear charge. It is, however, at first sight rather surprising that no evidence of the individual existence of protons in a nucleus is obtained from a study of the transformations of the radioactive elements, where the processes occurring must be supposed to be of a very fundamental character. As far as our observations have gone, electrons and helium nuclei, but no protons, are ejected during the long series of transformations of uranium, thorium and actinium. One of the most obvious methods for determining the structure of a nucleus is to find a method of disintegrating it into its component parts. This is done spontaneously for us by nature to a limited extent in the case of the heavy radioactive elements, but evidence of this character is not available in the case of the ordinary elements.

As the swift α particle from the radioactive bodies is, by far, the most energetic projectile known to us, it seemed from the first possible that occasionally the nucleus of a light atom might be disintegrated as the result of a close collision with an α particle. On account of the minute size of the nucleus, it is to be anticipated that the chance of a direct hit would be very small and that consequently the disintegration effects, if any, would be observed only on a very minute scale. During the last few years Dr. Chadwick and I have obtained definite evidence that hydrogen nuclei or protons can be removed by bombardment of α particles from the elements boron, nitrogen, fluorine, sodium, aluminum and phosphorus. In these experiments the presence of H nuclei is detected by the scintillation method, and their maximum velocity of ejection can be estimated from the thickness of matter which can be penetrated by these particles. The number of H nuclei ejected even in the most favorable case is relatively very small compared with the number of bombarding α particles, viz., about one in a million.

In these experiments the material subject to bombardment was placed immediately in front of the source of α particles

and observations on the ejected particles were made on a zinc sulphide screen placed in a direct line a few centimetres away. Using radium C as a source of α rays, the ranges of penetration, expressed in terms of centimetres of air, were all in these cases greater than the range of free nuclei (30 cms. in air) set in motion in hydrogen by the α particles. By inserting absorbing screens of 30 cms. air equivalent in front of the zinc sulphide screen the results were quite independent of the presence of either free or combined hydrogen as an impurity in the bombarded materials. Some of the lighter elements were examined for absorptions less than this, but, in general, the number of H particles due to hydrogen contamination of the source and the materials was so large that no confidence could be placed in the results.

In such experiments many scintillations can be observed, but it is very difficult to decide whether these can be ascribed in part to an actual disintegration of the material under examination. The presence of long-range particles of the α ray type from the source of radium C still further complicates the question, since in general the number of such particles is large compared with the disintegration effect we usually observe.

To overcome these difficulties, inherent in the direct method of observation, Dr. Chadwick and I have devised a simple method by which we can observe with certainty the disintegration of an element when the ejected particles have a range of only 7 cms. in air. This method is based on the assumption, verified in our previous experiments, that the disintegration particles are emitted in all directions relative to the incident rays. A powerful beam of α rays falls on the material to be examined and the liberated particles are observed at an average angle of 90° to the direction of the incident α particles. By means of screens it is arranged that no α particles can fall directly on the zinc sulphide screen.

This method has many advantages. We can now detect particles of range more than 7 cms. with the same certainty as particles of range above 30 cms. in our previous experi-

ments, for the presence of hydrogen in the bombarded material has no effect. This can be shown at once by bombarding a screen of paraffin wax, when no particles are observed on the zinc sulphide screen. On account of the very great reduction in number of H nuclei or α particles by scattering through 90°, the results are quite independent of H nuclei from the source or of the long-range α particles. The latter are just detectable under our experimental conditions when a heavy element like gold is used as scattering material, but are inappreciable for the lighter elements.

A slight modification of the arrangement enables us to examine gases as well as solids.

Working in this way we have found that in addition to the elements boron, nitrogen, fluorine, sodium, aluminum, and phosphorus, which give H particles of maximum range in the forward direction between 40 and 90 cms., the following give particles of range above 7 cms.: neon, magnesium, silicon, sulphur, chlorine, argon, and potassium. The numbers of the particles emitted from these elements are small compared with the number from aluminum under the same conditions, varying between $\frac{1}{3}$ and $\frac{1}{20}$. The ranges of the particles have not been determined with accuracy. Neon appears to give the shortest range, about 16 cms., under our conditions, the ranges of the others lying between 18 cms. and 30 cms. By the kindness of Dr. Rosenhain we were able to make experiments with a sheet of metallic beryllium. This gave a small effect, about $\frac{1}{30}$ of that of aluminum, but we are not yet certain that it may not be due to the presence of a small quantity of fluorine as an impurity. The other light elements, hydrogen, helium, lithium, carbon, and oxygen, give no detectable effect beyond 7 cms. It is of interest to note that while carbon and oxygen give no effect, sulphur, also probably a "pure" element of mass 4n, gives an effect of nearly one-third that of aluminum. This shows clearly that the sulphur nucleus is not built up solely of helium nuclei, a conclusion also suggested by its atomic weight of 32.07.

We have made a preliminary examination of the elements from calcium to iron, but with no definite results, owing to the difficulty of obtaining these elements free from any of the "active" elements, in particular, nitrogen. For example, while a piece of electrolytic iron gave no particles beyond 7 cms., a piece of Swedish iron gave a large effect, which was undoubtedly due to the presence of nitrogen, for after prolonged heating *in vacuo* the greater part disappeared. Similar results were experienced with the other elements in this region.

We have observed no effects from the following elements: nickel, copper, zinc, selenium, krypton, molybdenum, palladium, silver, tin, xenon, gold and uranium. The krypton and xenon were kindly lent by Dr. Aston.

EXAMINATION OF LIGHT ELEMENTS FOR PARTICLES OF RANGE LESS THAN 3 CMS. OF AIR

When α particles are scattered from light elements, the simple theory shows that the velocity of the scattered particles depends on the angle of scattering. For example, using bombarding α particles of range 7 cms., the range of the α particles scattered through more than 90° cannot be greater than 1.0 cm. for lithium (7), 2.0 cms. for beryllium (10), 2.5 cms. for carbon, 3.2 cms. for oxygen, 4.3 cms. for aluminum, and 6.8 cms. for gold.

Provided we introduce sufficient thickness of absorber to stop the α particles scattered through 90°, we can examine for disintegrated particles from carbon, for example, whose range exceeds 2.5 cms. Certain difficulties arise in this type of experiment which are absent when the thickness of absorber is greater than 7 cms.; any heavy element present as an impurity will give scattered α particles of range greater than those from carbon and thus complicate the observations. In addition, serious troubles may arise due to the volatilization or escape of active matter from the source. This is especially marked if the vessel containing the radioactive source

is exhausted. To overcome this difficulty, we have found it desirable to cover the source with a thin layer of celluloid of 2 or 3 m.m. stopping power for α rays. By this procedure we have been able to avoid serious contamination and to examine the lighter elements by this method. We have been unable to detect any appreciable number of particles from lithium or carbon for ranges greater than 3 cms. If carbon shows any effect at all, it is certainly less than one tenth of the number from aluminum under the same conditions. This is in entire disagreement with the work of Kirsch and Patterson (Nature, April 26, 1924), who found evidence of a large number of particles from carbon of range 6 cms. A slight effect was observed in beryllium in accordance with our other experiments. No effect was noted in oxygen gas. Apart from beryllium, no certain effect has been noted for elements lighter than boron.

Under the conditions of our experiment, it seems clear that neither H nuclei nor other particles of range greater than 3 cms. can be liberated in appreciable numbers from these elements in a direction at right angles to the bombarding α rays. This is, in a sense, a disappointing result, for, unless these elements are very firmly bound structures, it was to be anticipated that an α particle bombardment would resolve them into their constituent particles.

We hope to examine this whole question still more thoroughly, as it is a matter of great importance to the theory of nuclear constitution to be certain whether or not the light elements can be disintegrated by swift α particles.

In considering the results of our new and old observations, some points of striking interest emerge. In the first place, all the elements from fluorine to potassium inclusive suffer disintegration under α ray bombardment. As far as our observations have gone, there seems little doubt that the particles ejected from all these elements are H nuclei. The odd elements, B, N, F, Na, Al, P, all give long-range particles varying in range from 40 cms. to 90 cms. in the forward direction, the

even elements, C, O, Ne, Mg, Si, S, either give few particles or none at all as in the case of C and O, or give particles of much less range than the adjacent odd numbered elements. The differences between the ranges of even-odd elements become much less marked for elements heavier than phosphorus.

This obvious difference in velocity of expulsion of the H nuclei from even and odd elements is a matter of great interest. Such a distinction can be paralleled by other observations of an entirely different character. Harkins has shown that elements of even atomic number are much more abundant in the earth's crust than elements of odd atomic number. In his study of Isotopes, Aston has shown that in general odd numbered elements have only two isotopes differing in mass by two units, while even numbered elements in some cases contain a large number of isotopes. This remarkable distinction between even and odd elements cannot but excite a lively curiosity, but we can at present only speculate on its underlying cause.

VELOCITY OF ESCAPE OF HYDROGEN NUCLEI

We have seen that the experiments of Bieler on the scattering of α rays by aluminum and magnesium indicate that a powerful attractive force comes into play very close to the nuclei of these atoms. If this be the case, the forces of attraction and repulsion must balance at a certain distance from the nucleus. Outside this critical point the forces on a positively charged body are entirely repulsive. Certain important consequences follow from this general view of nuclear forces. Suppose, for example, that, due to a collision with a swift α particle, a hydrogen nucleus is liberated from the nuclear structure. After passing across the critical surface, it will acquire energy in passing through the repulsive field. It is clear, on this view, that the energy of a charged particle after escape from the atom cannot be less than the energy acquired in the repulsive field; consequently we should expect to find evidence that there is a minimum velocity of escape of a disintegration particle. We have obtained definite evidence of such an effect both in aluminum and sulphur by examining

the absorption of H nuclei from these elements. The number of scintillations for a thin film was found to be nearly constant for absorption between 7 and 12 cms., but falls off rapidly for greater thicknesses. This is exactly what is to be expected on the views outlined. No doubt the limiting velocity varies somewhat for the different elements, but a large amount of experiment will be required to fix this limit with accuracy. From these results it is possible to form a rough estimate of the potential of the field at the critical surface, and this comes out to be about 3 million volts for aluminum. The value for sulphur is somewhat greater. This brings out in a striking way the extraordinary smallness of the nuclei of these elements, for it can be calculated that the critical surface cannot be distant more than 6×10^{-13} cm. from the centre of the nucleus. These deductions of the critical distance are in excellent accord with those made by Bieler from observations of the scattering of α particles.

Another important consequence follows. It is clear that an α particle fired at the nucleus will not be able to cross this critical surface and thus be in a position to produce disintegration, unless its velocity exceeds that corresponding to the critical potential. In an experiment made a few years ago, we found that the number of H nuclei liberated from aluminum fell off rapidly with diminution of the velocity of the α particle and was too small in number to detect when the range of the α particle was less than 4.9 cms. This corresponds to the energy of an α particle falling between about 3 million volts —a value in good accord with that calculated from the escape of H nuclei.

Further experiments are required with other elements to test if this relation between the minimum velocity of H nuclei and the minimum velocity of the α particle to produce disintegration holds generally; but the results as far as they go are certainly very suggestive.

It is of interest to note that these results afford a definite proof of the nuclear conception of the atom and give us some

hope that we may determine the magnitude of the critical potential for a number of the light elements.

EVOLUTION OF NUCLEI

In concluding, I would like to make a few remarks of a more speculative character dealing with the fundamental problem of the origin and evolution of the elements from the two fundamental building units, the positive and negative electrons. It must be confessed that there is little information to guide us with the exception of our knowledge of the nuclear charges and masses of the various species of elements which survive to-day. It has always been a matter of great difficulty to imagine how the more complex nuclei can be built up by the successive additions of protons and electrons, since the proton must be endowed with a very high speed to approach closely to the charged nucleus. I have already discussed in this paper the evidence that powerful attractive forces varying very rapidly with the distance are present close to the nuclear structure and it seems probable that these forces must ultimately be ascribed to the constituent proton. In such a case it may be possible for an electron and proton to form a very close combination, or neutron, as I have termed it. The probable distance between the centre of this doublet is of the order of 3×10^{-13} cm. The forces between two neutrons would be very small except for distance of approach of this order of magnitude, and it is probable that the neutrons would collect together in much the same fashion as a number of small movable magnets would tend to form a coherent group held together by their mutual forces.

In considering the origin of the elements, we may for simplicity suppose a large diffused mass of hydrogen which is gradually heated by its gravitational condensation. At high temperatures the gas would consist mainly of free hydrogen nuclei and electrons, and some of these would in course of time combine to form neutrons, emitting energy in the process. These neutrons would collect together in nuclear masses of all kinds of complexity. Now the tendency of the groups of

neutrons would be to form more stable nuclear combinations, such as helium nuclei of mass four, and possibly intermediate stages of masses two and three. Energy would be emitted in these processes probably in the form of swift surplus electrons which were not necessary for the stability of the system. In a sense, all these nuclear masses would be radioactive, but some of them in their transformation may reach a stable configuration which would represent the nucleus of one of our surviving elements. If we suppose that nuclear masses over a wide range of mass can be formed before serious transformation occurs, it is easy to see how every possible type of stable element will gradually emerge. If we take the helium nucleus as a combining unit which emits in its formation the greatest amount of energy, we should ultimately expect many of the neutrons in a heavy nucleus to form helium nuclei. These helium nuclei would tend to collect together and form definite systems and it seems not unlikely that they will group themselves into orderly structures, analogous in some respects to the regular arrangement of atoms to form crystals, but with much smaller distances between the structural units. In such a case, some of the elements may consist of a central crystal type of structure of helium nuclei surrounded by positive and negatively charged satellites in motion round this central core. Assuming that such orderly arrangements of helium nuclei are possible, it is of interest to note that the observed relations between atomic charge and atomic mass for the elements can be approximately obtained on a very simple assumption. Suppose that helium nuclei form a point centred cubic lattice with an electron at the centre of a crystal unit of eight helium nuclei. A few of the possible types of grouping are given in the following table, with corresponding masses and nuclear charges. The structure 4.3.2. means a rectangular arrangement with sides containing 4.3.2. nuclei respectively. It will thus contain 24 helium nuclei, have a mass 96, and will contain 6 intranuclear electrons. Its nuclear charge will therefore be 48 - 6 = 42.

Structural arrangement of helium nuclei	Calculated nuclear charge	Calculated Mass	Known element of equal charge
3. 2. 2.	22	48	Ti 48
3. 3. 2.	32	72	Ge 74, 72, 70
3. 3. 3.	46	108	Pd 106.7
4. 2. 2.	29	64	Cu 63.35
4. 3. 2.	42	96	Mo 96
4. 3. 3.	60	144	Nd 144
4. 4. 3.	78	192	Pt 195

While the agreement is far from perfect for all these structures, there is a general accord with observation. If we take the view that some of these structures can grow by the addition of satellites, there is room for adjustment of masses and to include the intervening elements. This point of view is admittedly very speculative and there may well be other types of structure involved. At the same time, the general evidence suggests that there are some basal structures on which the heavier atoms are progressively built up. The failure of the whole number rule for the mass of isotopes, observed in some cases by Aston, *e.g.*, between tin and xenon, certainly supports such a conception. From a study of the artificial disintegration of the elements we have seen that carbon and oxygen represent very stable structures probably composed of helium nuclei. It is possible that oxygen nuclei, for example, may be the structural basis of some of the elements following oxygen, but our information is at present too meagre to be at all certain on this point.

I think, however, it will be clear from this lecture what a difficult but fascinating problem is involved in the structure of nuclei. Before we can hope to make much advance, it is essential to know more of the nature of the forces operative close to protons and electrons, and we may hope to acquire much information by a detailed study of the scattering of swift α rays and β rays by nuclei. Fortunately, there is now a number of distinct lines of attack on this problem, and from a combination of the results obtained we may hope to make steady, if not rapid, progress in the solution of this, the greatest problem in Physics.